Cosmic inflation

Superhorizon fluctuations exacerbate horizon problem

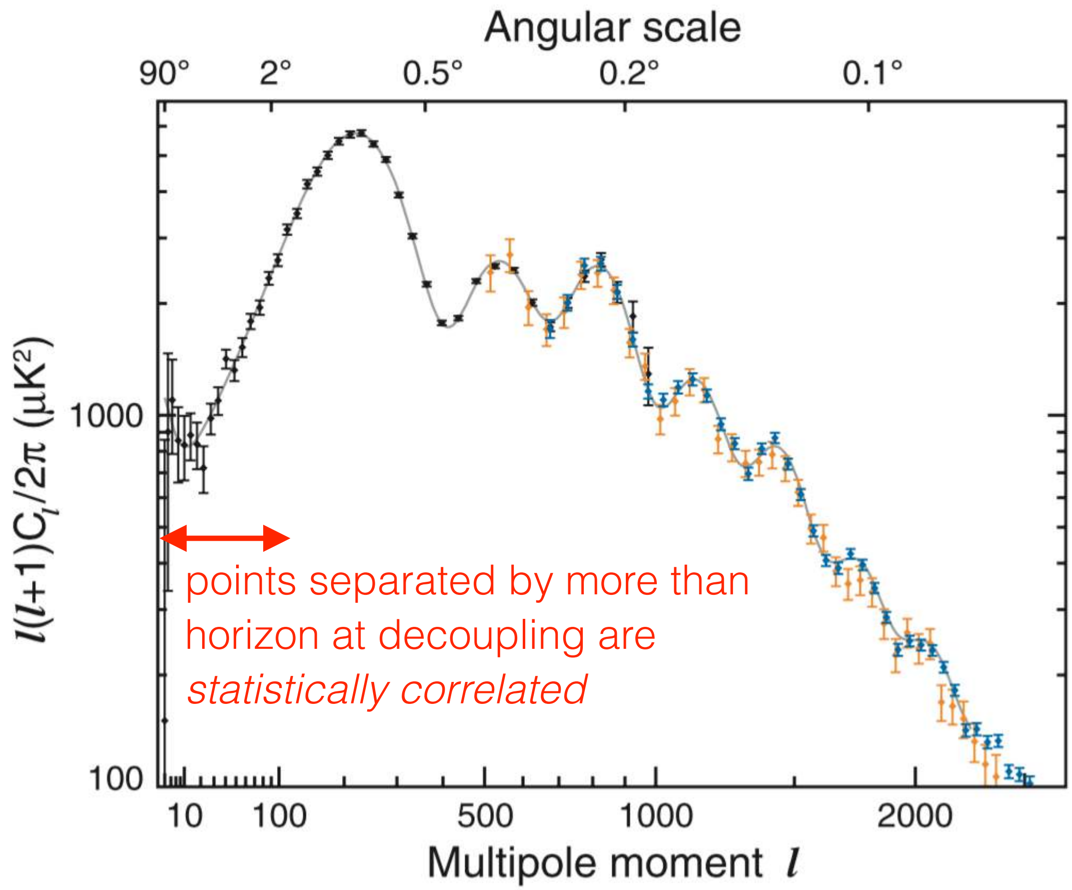

Figure 1. Compilation of the CMB data used in the nine-year *WMAP* analysis. The *WMAP* data are shown in black, the extended CMB data set—denoted "eCMB" throughout—includes SPT data in blue (Keisler et al. 2011) and ACT data in orange, (Das et al. 2011b). We also incorporate constraints from CMB lensing published by the SPT and ACT groups (not shown). The ΛCDM model fit to the *WMAP* data alone (shown in gray) successfully predicts the higher-resolution data.

(A color version of this figure is available in the online journal.)

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Inflationary universe: A possible solution to the horizon and flatness problems

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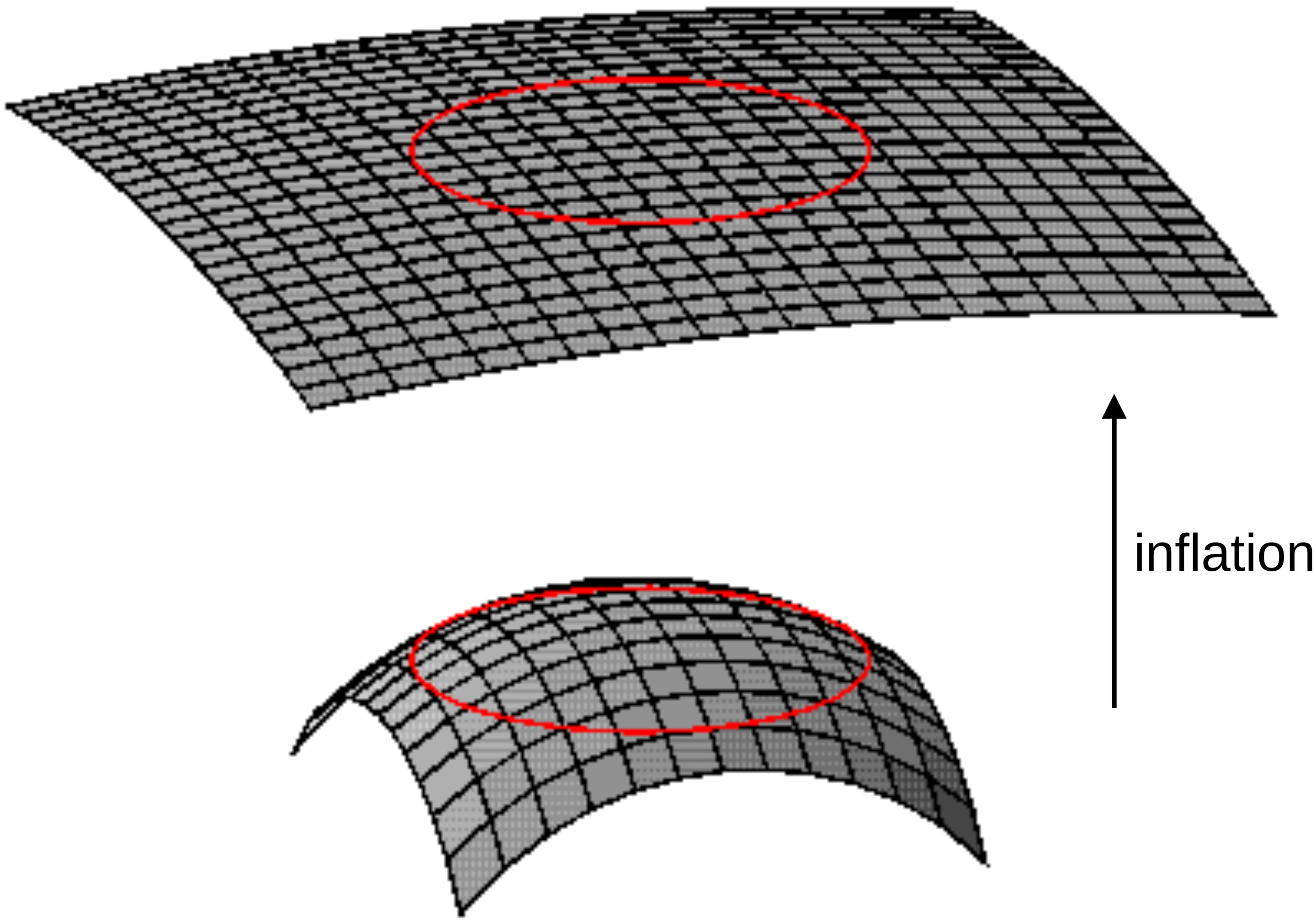
The standard model of hot big-bang cosmology requires initial conditions which are problematic in two ways: (1) The early universe is assumed to be highly homogeneous, in spite of the fact that separated regions were causally disconnected (horizon problem); and (2) the initial value of the Hubble constant must be fine tuned to extraordinary accuracy to produce a universe as flat (i.e., near critical mass density) as the one we see today (flatness problem). These problems would disappear if, in its early history, the universe supercooled to temperatures 28 or more orders of magnitude below the critical temperature for some phase transition. A huge expansion factor would then result from a period of exponential growth, and the entropy of the universe would be multiplied by a huge factor when the latent heat is released. Such a scenario is completely natural in the context of grand unified models of elementary-particle interactions. In such models, the supercooling is also relevant to the problem of monopole suppression. Unfortunately, the scenario seems to lead to some unacceptable consequences, so modifications must be sought.

Inflationary solution to the flatness problem



During inflation, Universe expands much faster than the horizon (red circle). For observers within the horizon, the Universe becomes indistinguishable from exact flatness.

Credit: E. Wright

Inflationary solution to the horizon problem

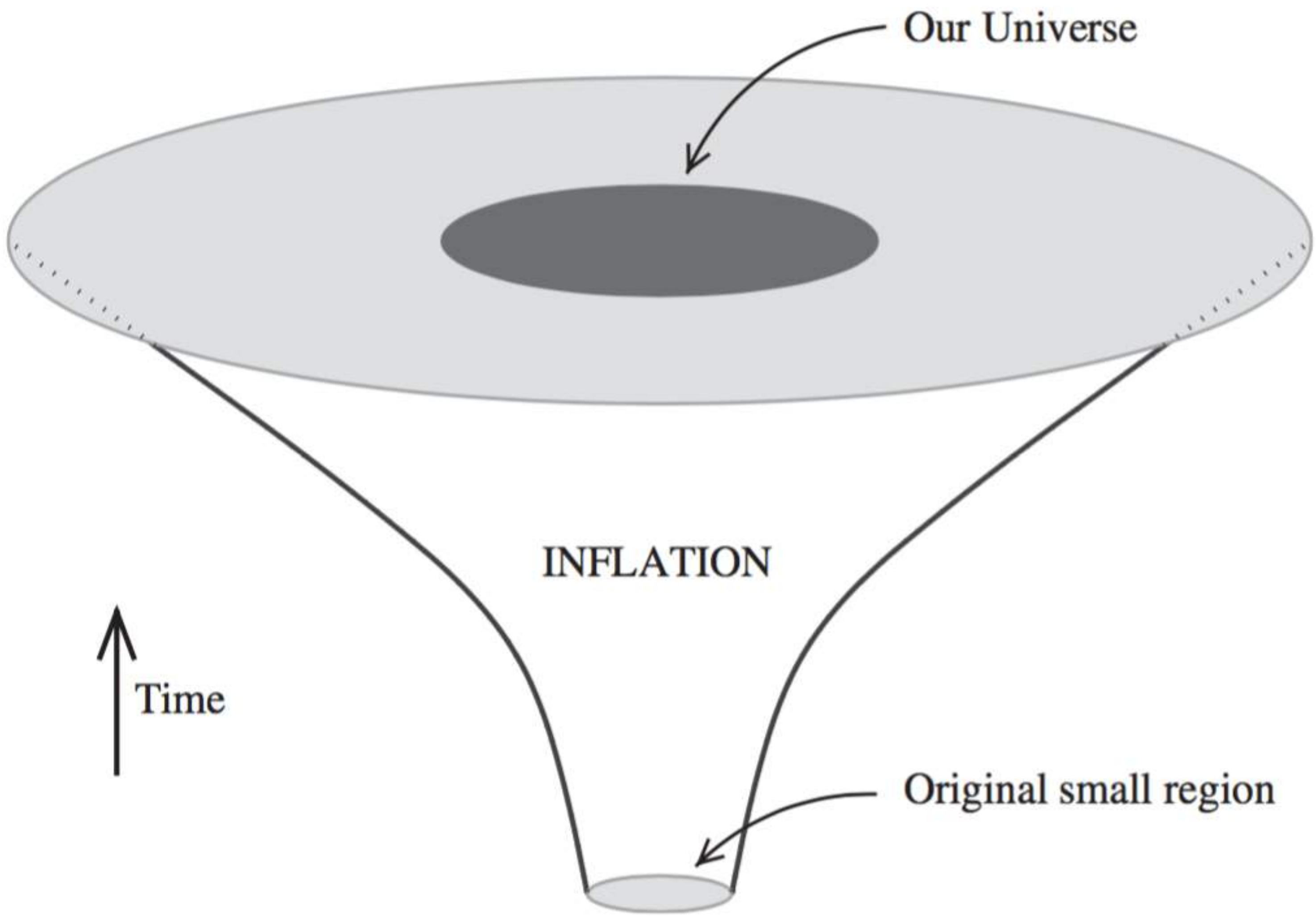


Figure 13.3 A schematic illustration of the inflationary solution to the horizon problem, with a small initial thermalized region blown up to encompass our entire observable Universe.

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Shortly after inflation was proposed, it was shown that it can also account for initial perturbations capable of growing into galaxies

THE DEVELOPMENT OF IRREGULARITIES IN A SINGLE BUBBLE INFLATIONARY UNIVERSE

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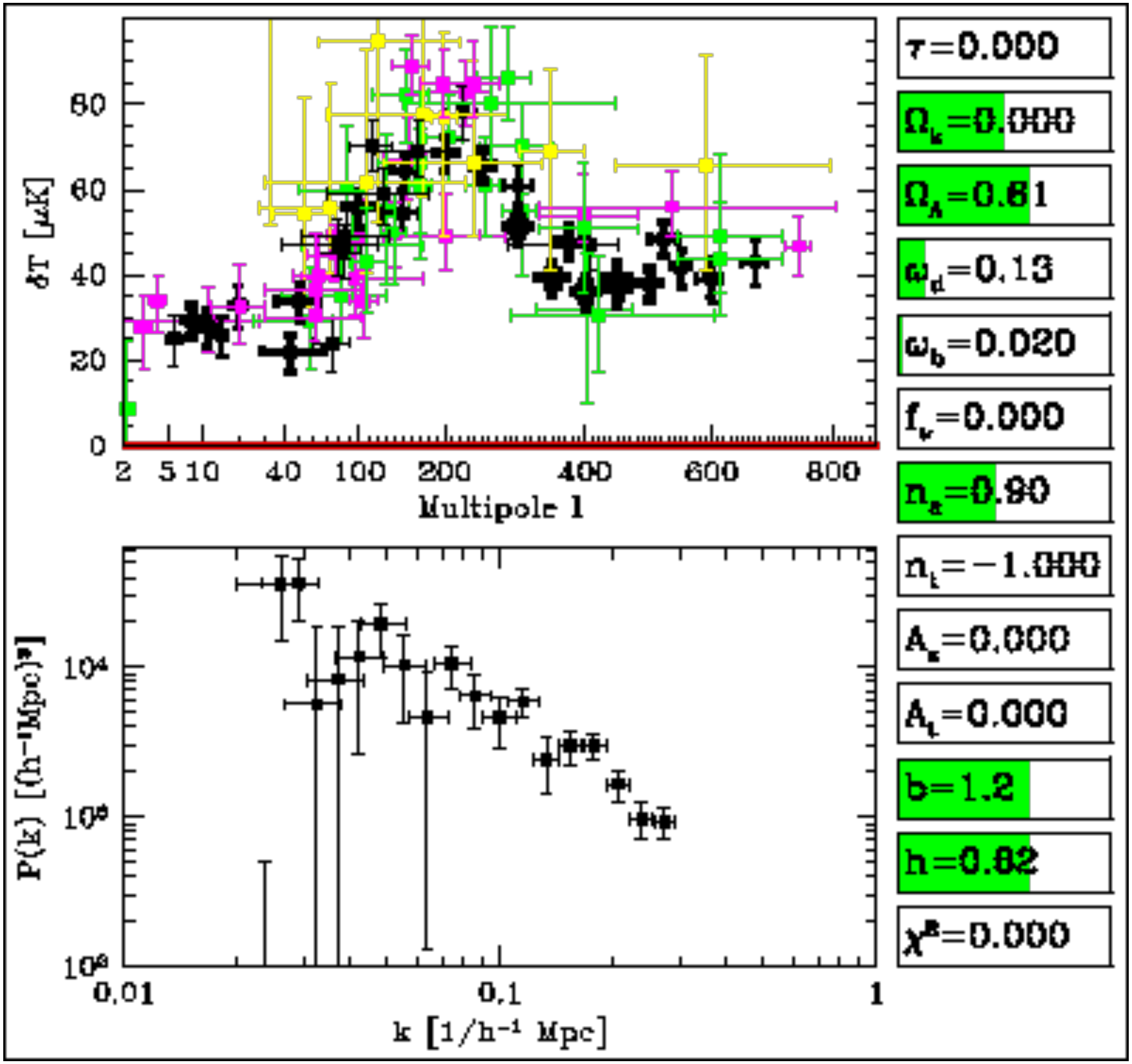
The horizon, flatness and monopole problems can be solved if the universe underwent an exponentially expanding stage which ended with a Higgs scalar field running slowly down an effective potential. In the downhill phase irregularities would develop in the scalar field. These would lead to fluctuations in the rate of expansion which would have the right spectrum to account for the existence of galaxies. However the amplitude would be too high to be consistent with observations of the isotropy of the microwave background unless the effective coupling constant of the Higgs scalar was very small.

and contemporaneous papers by

- Mukhanov & Chibisov (1981)
- Starobinsky (1982)
- Guth & Pi (1982)
- Bardeen, Steinhardt, & Turner (1983)

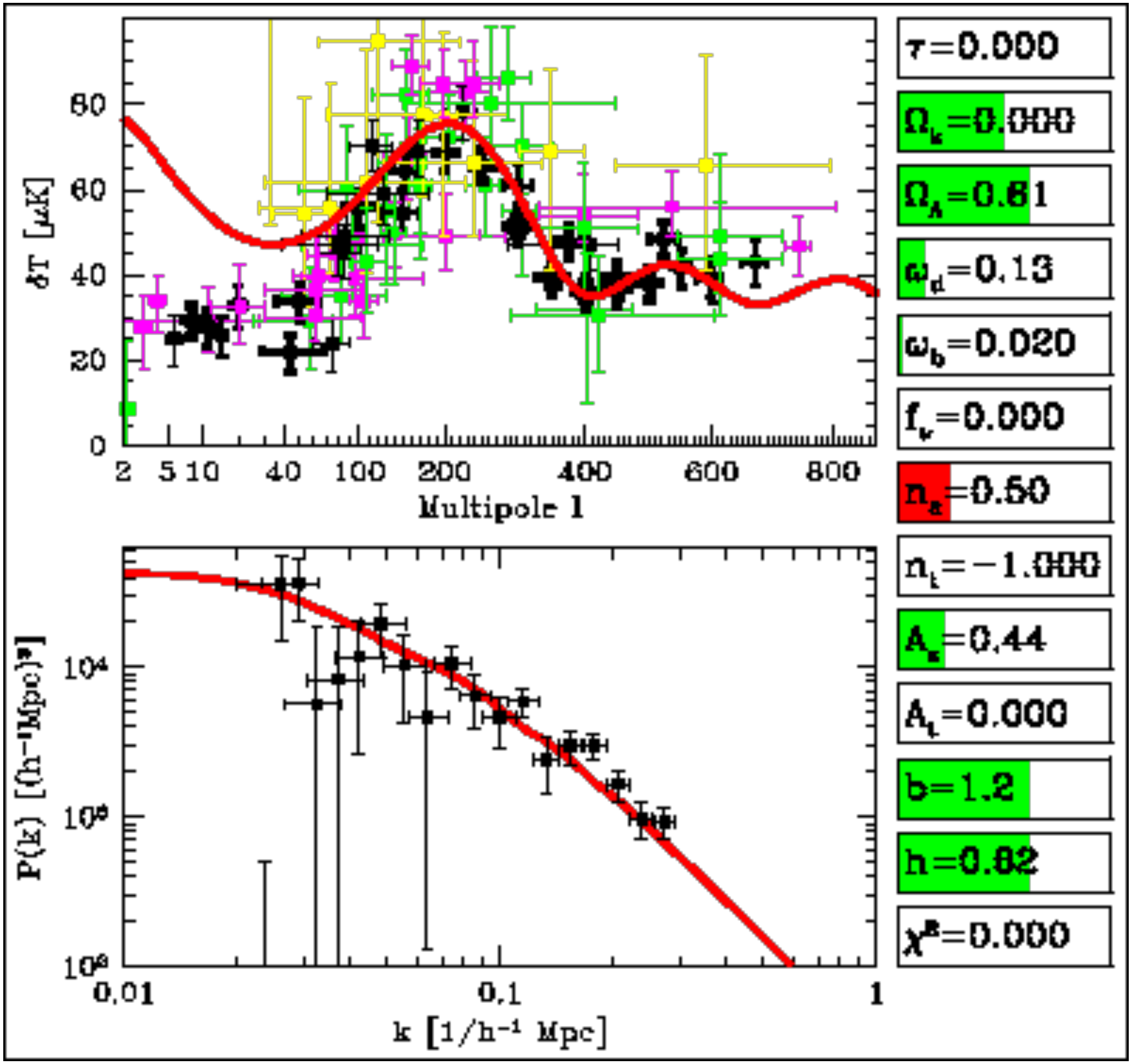
Varying amplitude of primordial power spectrum



$\omega_X \equiv \Omega_X h^2$

Credit: M. Tegmark

Varying spectral index of primordial power spectrum



$\omega_X \equiv \Omega_X h^2$

Credit: M. Tegmark

NINE-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE* (*WMAP*) OBSERVATIONS: COSMOLOGICAL PARAMETER RESULTS

ABSTRACT

We present cosmological parameter constraints based on the final nine-year *Wilkinson Microwave Anisotropy Probe* (*WMAP*) data, in conjunction with a number of additional cosmological data sets. The *WMAP* data alone, and in combination, continue to be remarkably well fit by a six-parameter ΛCDM model. When *WMAP* data are combined with measurements of the high-l cosmic microwave background anisotropy, the baryon acoustic oscillation scale, and the Hubble constant, the matter and energy densities, $\Omega_b h^2$, $\Omega_c h^2$, and Ω_Λ, are each determined to a precision of ~1.5%. The amplitude of the primordial spectrum is measured to within 3%, and there is now evidence for a tilt in the primordial spectrum at the 5σ level, confirming the first detection of tilt based on the five-year *WMAP* data. At the end of the *WMAP* mission, the nine-year data decrease the allowable volume of the six-dimensional ΛCDM parameter space by a factor of 68,000 relative to pre-*WMAP* measurements. We investigate a number of data combinations and show that their ΛCDM parameter fits are consistent. New limits on deviations from the six-parameter model are presented, for example: the fractional contribution of tensor modes is limited to $r < 0.13$ (95% CL); the spatial curvature parameter is limited to $\Omega_k = -0.0027^{+0.0039}_{-0.0038}$; the summed mass of neutrinos is limited to $\sum m_\nu < 0.44$ eV (95% CL); and the number of relativistic species is found to lie within $N_{\rm eff} = 3.84 \pm 0.40$, when the full data are analyzed. The joint constraint on $N_{\rm eff}$ and the primordial helium abundance, $Y_{\rm He}$, agrees with the prediction of standard big bang nucleosynthesis. We compare recent *Planck* measurements of the Sunyaev–Zel'dovich effect with our seven-year measurements, and show their mutual agreement. Our analysis of the polarization pattern around temperature extrema is updated. This confirms a fundamental prediction of the standard cosmological model and provides a striking illustration of acoustic oscillations and adiabatic initial conditions in the early universe.

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The six parameters of the standard ΛCDM cosmological model

Table 2
Maximum Likelihood ΛCDM Parameters[a]

Parameter	Symbol	*WMAP* Data	Combined Data[b]
		Fit ΛCDM Parameters	
Physical baryon density	$\Omega_b h^2$	0.02256	0.02240
Physical cold dark matter density	$\Omega_c h^2$	0.1142	0.1146
Dark energy density ($w = -1$)	Ω_Λ	0.7185	0.7181
Curvature perturbations, $k_0 = 0.002$ Mpc^{-1}	$10^9 \Delta^2_{\mathcal{R}}$	2.40	2.43
Scalar spectral index	n_s	0.9710	0.9646
Reionization optical depth	τ	0.0851	0.0800
		Derived Parameters	
Age of the universe (Gyr)	t_0	13.76	13.75
Hubble parameter, $H_0 = 100\,h$ km s^{-1} Mpc^{-1}	H_0	69.7	69.7
Density fluctuations @ 8 h^{-1} Mpc	σ_8	0.820	0.817
Baryon density/critical density	Ω_b	0.0464	0.0461
Cold dark matter density/critical density	Ω_c	0.235	0.236
Redshift of matter-radiation equality	z_{eq}	3273	3280
Redshift of reionization	z_{reion}	10.36	9.97

Notes.
[a] The maximum-likelihood ΛCDM parameters for use in simulations. Mean parameter values, with marginalized uncertainties, are reported in Table 4.
[b] "Combined data" refers to *WMAP*+eCMB+BAO+H_0.

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The six parameters of ΛCDM simultaneously fit a much larger number of data points, e.g. CMB power spectrum

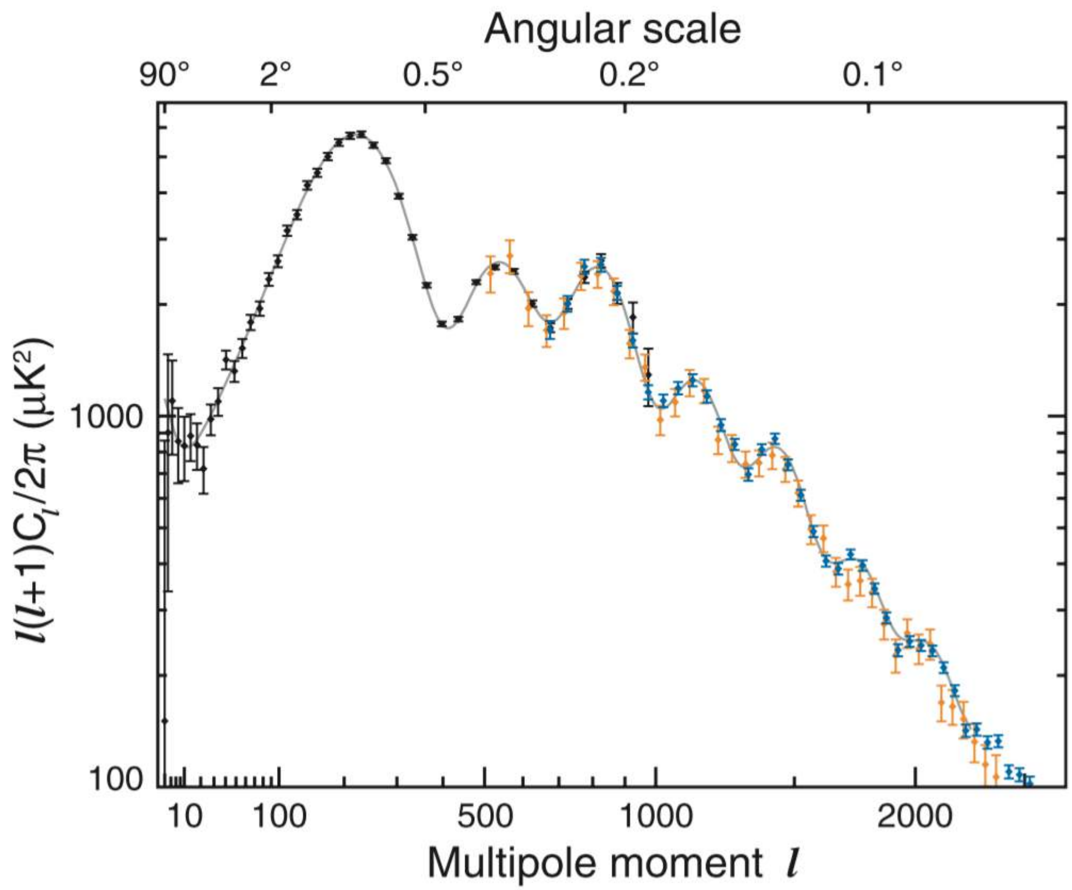

Figure 1. Compilation of the CMB data used in the nine-year *WMAP* analysis. The *WMAP* data are shown in black, the extended CMB data set—denoted "eCMB" throughout—includes SPT data in blue (Keisler et al. 2011) and ACT data in orange, (Das et al. 2011b). We also incorporate constraints from CMB lensing published by the SPT and ACT groups (not shown). The ΛCDM model fit to the *WMAP* data alone (shown in gray) successfully predicts the higher-resolution data.

(A color version of this figure is available in the online journal.)

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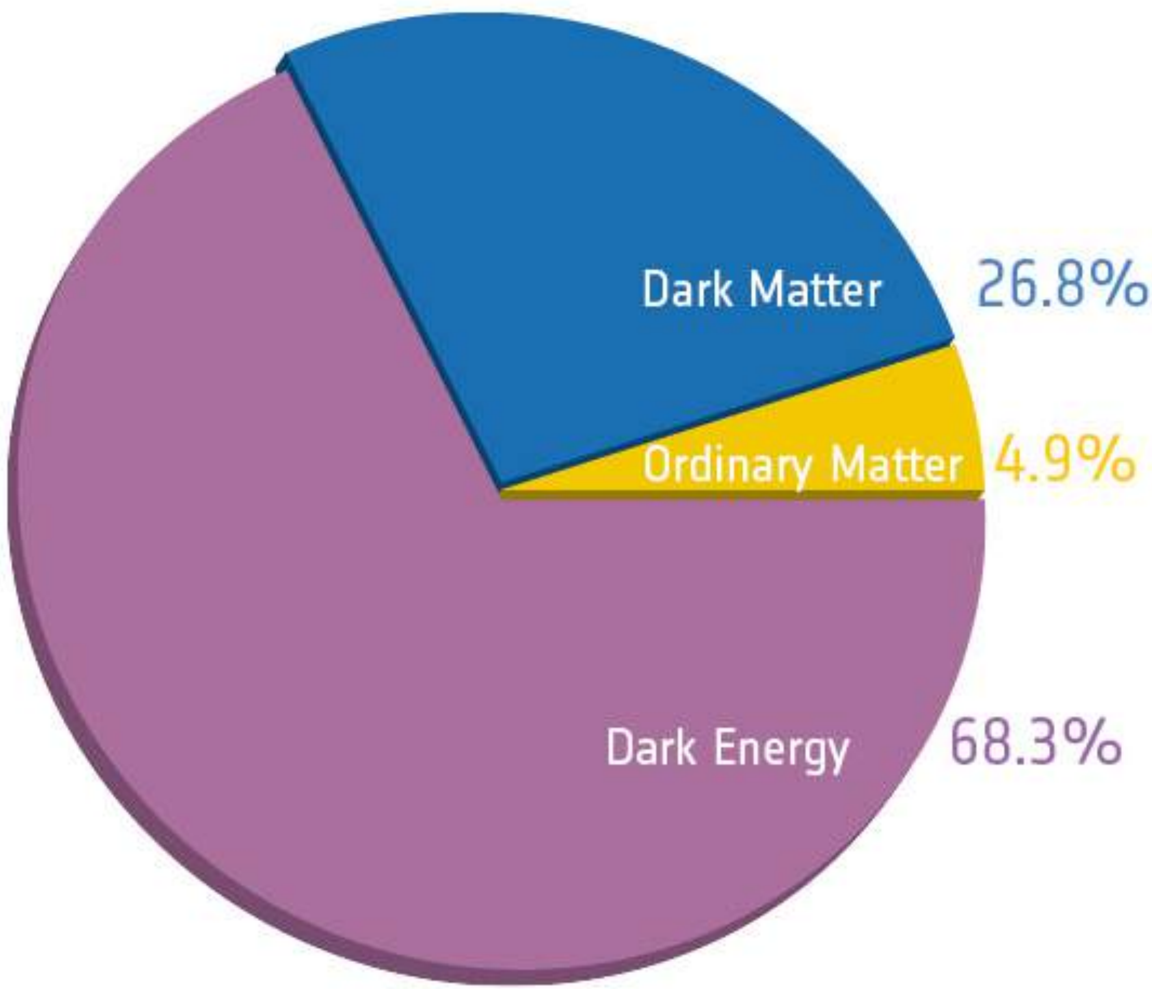
Conclusion: inflationary ΛCDM cosmology is an *excellent fit* but still *much physics to be understood*



- Excellent fit to large number of observations (CMB, SNe, BAOs, light elements, gravitational lensing, galaxy rotation curves, growth of structure, …)

- But all main elements (DE, DM, inflation) of unknown physical origin!

Planck 2013

Extra slides

Spheres of influence

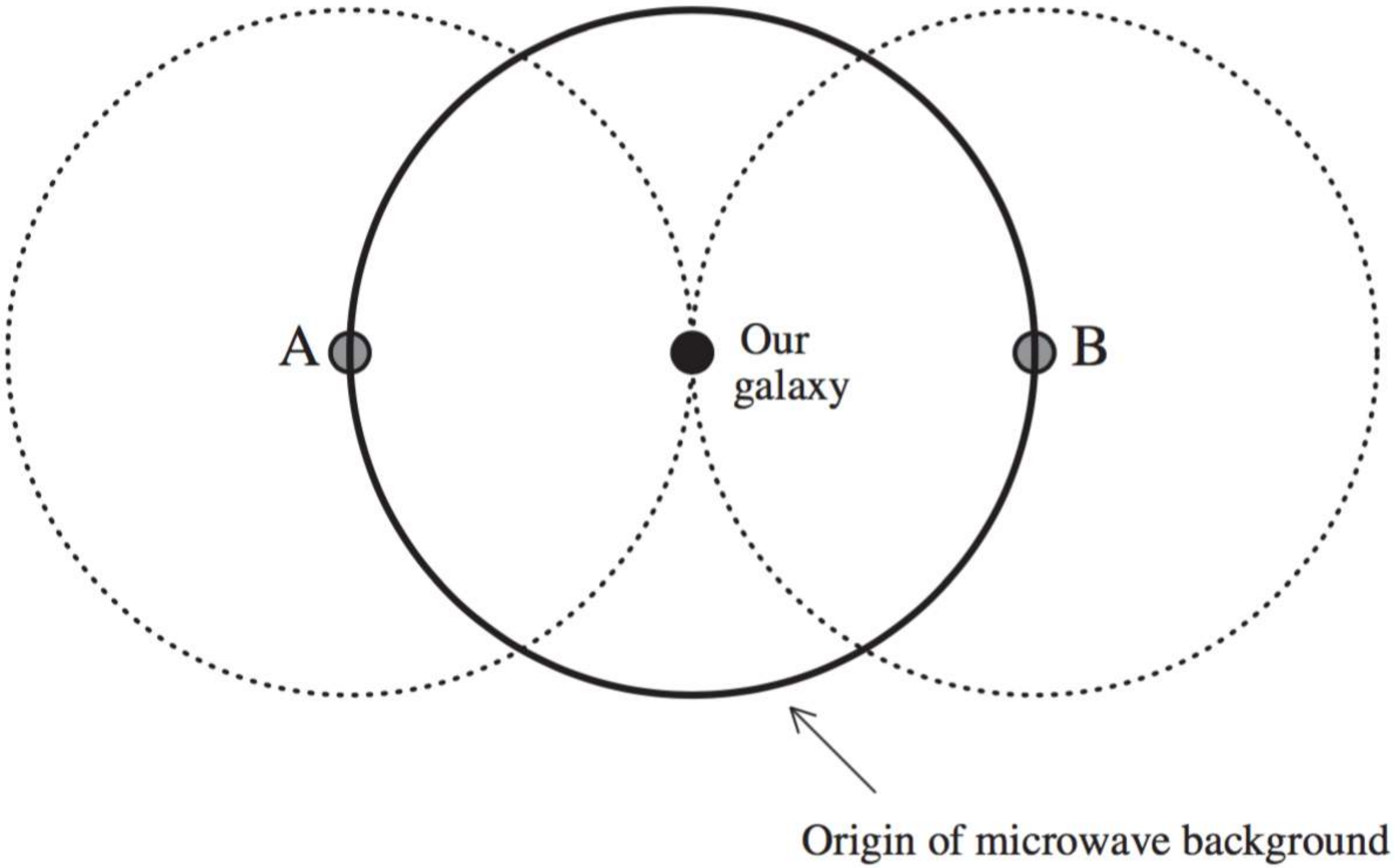


Figure 13.1 An illustration of the horizon problem. We receive microwave radiation from points **A** and **B** on opposite sides of the sky. These points are well separated and would not have been able to interact at all since the Big Bang – the dotted lines indicate the extent of regions able to influence points **A** and **B** by the present – far less manage to interact by the time the microwave radiation was released. So in the Hot Big Bang model it is impossible to explain why they have the same temperature to such accuracy.

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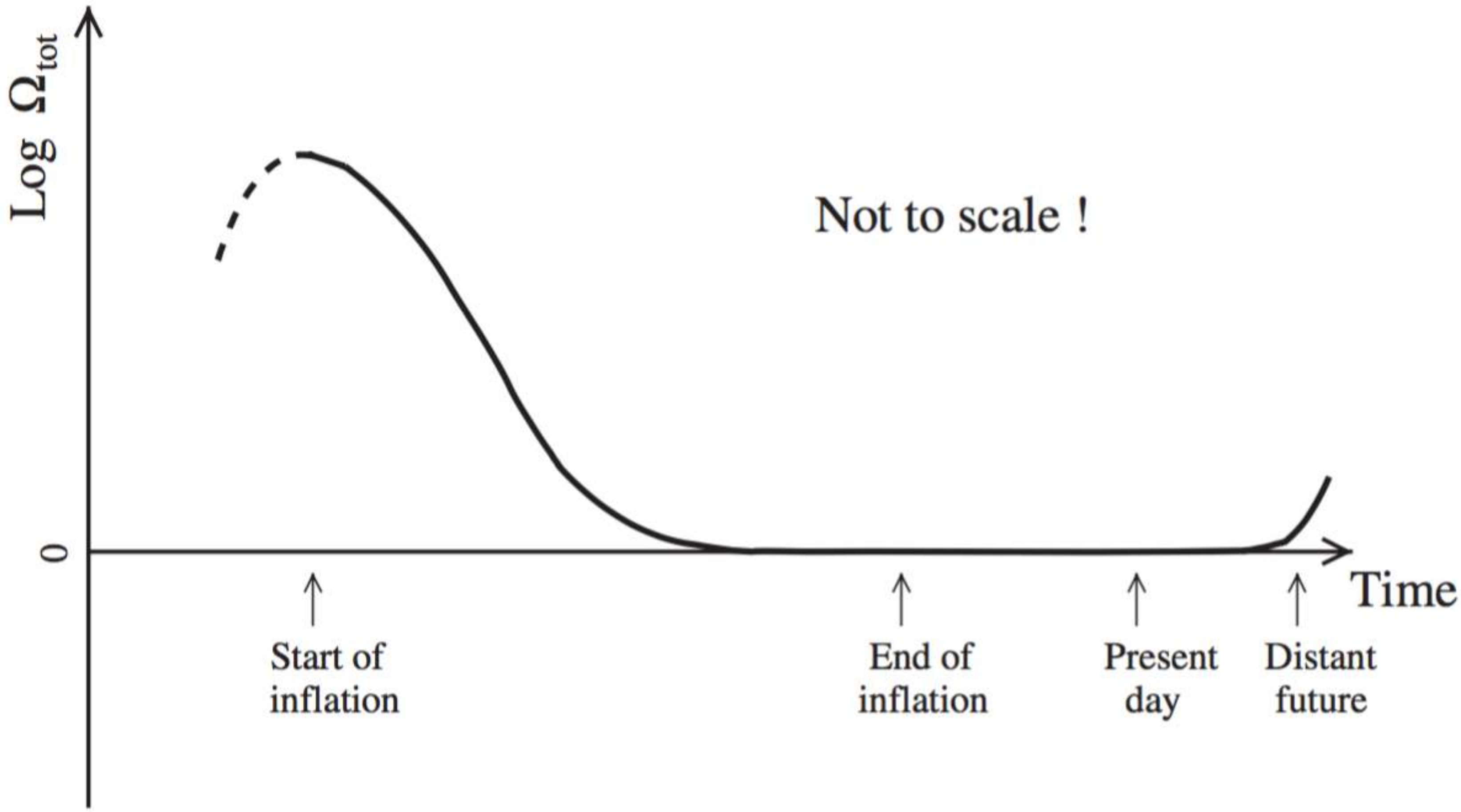

Figure 13.2 Possible evolution of the density parameter Ω_{tot}. There might or might not be a period before inflation, indicated by the dashed line. Inflation then drives $\log \Omega_{\mathrm{tot}}$ towards zero (i.e. Ω_{tot} towards 1), either from above or below. By the time inflation ends Ω_{tot} is so close to one that all the evolution after inflation up to the present day is not enough to pull it away again. Only some time in the very distant future would it start to move away from one again.

Liddle

Quantum fluctuations and a nonsingular universe

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(Submitted 26 February 1981; resubmitted 15 April 1981)

Pis'ma Zh. Eksp. Teor. Fiz. **33**, No. 10, 549–553 (20 May 1981)

Over a finite time, quantum fluctuations of the curvature disrupt the nonsingular cosmological solution corresponding to a universe with a polarized vacuum. If this solution held as an intermediate stage in the evolution of the universe, then the spectrum of produced fluctuations could have led to the formation of galaxies and galactic clusters.

DYNAMICS OF PHASE TRANSITION IN THE NEW INFLATIONARY UNIVERSE SCENARIO AND GENERATION OF PERTURBATIONS

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Dynamics of non-equilibrium phase transition in the early universe is investigated. The transition is triggered by vacuum fluctuations of a Higgs scalar field which determine the duration of an intermediate inflationary stage and the amplitude of adiabatic perturbations. This amplitude ranges from g^2 to one and more depending on scale that presents a serious problem for the inflationary scenario.

Fluctuations in the New Inflationary Universe

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(Received 9 August 1982)

The spectrum of density perturbations is calculated in the new-inflationary-universe scenario. The main source is the quantum fluctuations of the Higgs field, which lead to fluctuations in the time at which the false vacuum energy is released. The value of $\delta\rho/\rho$ on any given length scale l, at the time when the Hubble radius $\gg l$, is estimated. This quantity is nearly scale invariant (as desired), but is unfortunately about 10^5 times too large.

PACS numbers: 98.80.Bp, 12.10.En, 98.50.Eb, 98.80.Dr

Spontaneous creation of almost scale-free density perturbations in an inflationary universe

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The creation and evolution of energy-density perturbations are analyzed for the "new inflationary universe" scenario proposed by Linde, and Albrecht and Steinhardt. According to the scenario, the Universe underwent a strongly first-order phase transition and entered a "de Sitter phase" of exponential expansion during which all previously existing energy-density perturbations expanded to distance scales very large compared to the size of our observable Universe. The existence of an event horizon during the de Sitter phase gives rise to zero-point fluctuations in the scalar field ϕ, whose slowly growing expectation value signals the transition to the spontaneous-symmetry-breaking (SSB) phase of a grand unified theory (GUT). The fluctuations in ϕ are created on small distance scales and expanded to large scales, eventually giving rise to an almost scale-free spectrum of adiabatic density perturbations (the so-called Zel'dovich spectrum). When a fluctuation reenters the horizon

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